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Report No. 181

WATER PENETRATION INTO THE FOOT

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Research and Development Branch

Military Planning Division

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OFFICE OF THE QUARTERMASTER GENERAL

Military Planning Division

Research and Development Branch

Environmental Protection Section

Report No. 181

PENETRATION OF WATER INTO THE HUMAN FOOT

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PENETRATION OF WATER INTO THE HUMAN FOOT

Abstract

Purpose

To study the moisture and temperature relationships between the foot and its immediate environment.

Summary

The surprising fact that men can wear impermeable barriers or all-rubber shoepacs for several days without discomfort has been shown by Siple and Bazett,[41] Spealman,[5] Clinton,[2] Folk and Peary,[13] and Blair.[6]

It was demonstrated in EPS Special Report No. 37, that the amount of moisture accumulated under an impermeable barrier was modified by the thickness of the absorbent layer between the skin of the foot and the impermeable barrier. The accumulation of foot perspiration is appreciably less when an impermeable barrier is worn outside the innermost of three pairs of socks ("near" barrier) than when the barrier is worn outside three pairs ("far" barrier). In some cases the amount of sweat accumulated under the "far" barrier was four or five times that accumulated under the "near" barrier. Evidence was presented which suggested that repenetration rather than suppression of sweating was the mechanism limiting sweat accumulation.

The perspiration which accumulates in three socks under a "far" barrier, or in five socks is only a part of the perspiration which would be evaporating from the foot if no sockgear were present. Probably the repenetration phenomenon takes place under other types of footgear as well as the impermeable sock. Furthermore, it was found that this phenomenon occurs in the hands when they are dressed in "near" barriers.

Wear of an impermeable barrier over a single sock is not associated with discomfort, the sock does not become excessively wet, and only limited quantities of moisture can be found on the skin or sock when the latter is removed. Apparently repenetration of water for several days does not alter the performance or comfort of the human foot. In one test eleven men wearing "near" and "far" barriers and shoepacs completed a strenuous mountain climb without appreciable foot discomfort. The impermeable barriers worn by four of the men for 48 hours prior to the climb had caused continuous repenetration during this period.

Evidence for the occurrence of repenetration under impermeable barriers was also obtained by prewetting socks worn under impermeable barriers. One series with presoaking was carried out with 90 cc. of water in the socks at beginning of the experiment. As much as 37 cc. of this water penetrated the skin during the 10-hour experimental period. These studies showed a measured penetration of approximately 1 cc. of water per hour from moderately wet socks into the feet of sitting subjects, and a measured penetration of 2 cc. to 3 cc. per hour for eight to ten hours from wet socks with subjects walking part of the time. It was supposed that this measured penetration represented only one component of the actual value. The remainder would originate from continuous sweating which would supposedly increase the fluid content of wet socks unless penetration occurred. It is significant that 20 minutes after a wet and a dry sock were applied on opposite feet, the subject frequently could not detect a difference in sensation of wetness between the two feet.

The occurrence of repenetration under the "near" barrier could be established by evidence that sweating continued at its normal rate. Chloride analysis of perspiration collected in the socks was used as a measure of sweating. When subjects wore "near" barriers under three different types of conditions, tests for chloride secretion demonstrated that approximately normal sweating continues under the "near" barrier. When subjects wore a dry sock on one foot and a watersoaked sock on the other foot for several days, the chloride collections from the two socks appeared similar. The observations that sweat chlorides were collected in similar quantities in both wet and dry socks, under "near" and "far" barriers, and in a water bath compared with sock control values, suggest that sweating continues at normal rates under "near" barriers.

The measured vapor pressure in socks under both a "near" and a "far" barrier was in nearly all cases lower than the calculated vapor pressure in the associated skin tissue. Apparently with this footgear a suppression effect on the diffusion of insensible moisture does not usually occur.

Thus the relationships under the "near" barrier seem to be such that water in the sock, whether it originates from external sources, by accumulation from sweat glands, or as insensible moisture, comes to an equilibrium value in a few hours, apparently due to repenetration.

It is usually assumed that footwear designed for protracted wear must provide for evaporation of sweat. These studies have shown that evaporation is not essential inside a shoe, and that, therefore, footwear which preserves its insulation by virtue of being water-impermeable on both the inside and the outside may be physiologically acceptable.

Conclusions

Penetration of water from wet socks into the foot has been demonstrated, explaining the acceptability of impermeable footwear.

Less sweat accumulates under an impermeable barrier which is placed near the foot (over one sock) than under a barrier placed at a greater distance from the foot.

As measured by sweat chloride, production of sweat is not suppressed by an impermeable barrier but continues at an approximately normal rate. The reduced accumulation reflects an equilibrium reached between production and repenetration.

Socks worn under impermeable barriers do not become excessively wet. The skin under such barriers does not become completely sodden, and discomfort, if any, is transient.

Preliminary studies of vapor pressure under different layers of socks indicate that the vapor pressure does not reach that calculated for tissue even though repenetration of moisture is occurring.

The phenomenon of repenetration probably occurs under leather footwear as well as under impermeable rubber or plastic barriers. Footwear maintaining insulation by virtue of sealed-in insulation is physiologically acceptable.

Recommendations

That further studies of the two-way passage of water through the skin be undertaken in relation to impermeable footgear, including studies at lower skin temperatures.

That these studies be extended to other areas of the body, especially as they may apply to the study of vapor barrier clothing.

That additional techniques be employed in studying the mechanisms of this surprising phenomenon. Particular attention should be given to the electrolyte composition of the water which repenetrates.

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FOREWORD

Under the contract between the Quartermaster Corps and Bowdoin College, Dr. Folk has obtained information with considerable theoretical interest and information having many implications for practical development and design concept in footwear construction. The findings suggest many lines of investigation which should be pursued further.

As Dr. Folk has indicated, impermeable footgear developed to provide sealed-in insulation were surprisingly acceptable, and the expectation that the subjects would be walking in a puddle of sweat did not materialize. His findings provide an explanation of the mechanism which limits fluid accumulation when the foot is surrounded by impermeable materials.

Dr. Folk's work illustrates one of the contributions that the experimental scientist can make as part of a team concerned with practical development -- namely, the reassessment of the axioms or basic assumptions upon which development is consciously or unconsciously based. The axiom that the footwear must be designed to let sweat evaporate from the foot is hereby forced to undergo extensive modification.

Future investigation along these lines in the Climatic Research Laboratory program will include extension of studies on the temperature and vapor pressure relationships at the skin surface, in the sock fabric, and at the barrier surface. The observations will be extended to include isotopic tracer studies of the sweat electrolytes, more direct studies on the path of repenetration, and the effect of socks of different water repellency and wicking properties.

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PENETRATION OF WATER INTO THE HUMAN FOOT

1. Introduction

A study of the moisture and temperature relationships between the foot and its immediate environment has been made at Bowdoin College over the past two years. This program was initiated because of the dearth of information concerning foot physiology, and because it was believed that many of the assumptions concerning foot function are erroneous. Investigations of the temperature regulation of the human foot are few, and much of the information which is supposed to apply to "the human extremities" has been gathered only from the human hand. The assumption has frequently been made that the regulatory mechanisms found in the foot are usually closely linked with those of the hand. The commonly used term "palmar-sole sweating" is indicative of this supposed association.

That there is coordinated function of the extremities has been demonstrated by warming and cooling the feet with resulting reflex warming or cooling of the hands. Theoretical explanation of this reflex mechanism depends in part upon vasomotor control of the hands and feet by the central nervous system.[31,33,34,40,46] The fingers and toes are similar in possessing arterio-venous shunts and behave similarly in that they have a high skin temperature with a high rate of blood flow when heat loss from the body must be facilitated, and low skin temperature and low rate of blood flow at times when central body heat is being conserved.[38] Functionally, however, the extremities are in part independent. Roth[35] and Abramson[1] have shown that the hand and foot do not necessarily respond simultaneously to vasomotor stimuli,[14,15] and they do not respond in the same manner to "psychic sweat" stimuli.

In contrast to the hands, the feet are usually clothed and support part or all of the body weight. The vascular relationships in the foot may be affected by higher venous pressures than those of the hand. Being clothed, the moistness of the skin of the foot will usually be greater than that of the hand.

The moisture relationships between the foot and footgear have received the attention of applied physiologists for several years. The surprising fact that men can wear impermeable barriers or all-rubber shoepacs for protracted periods of time without discomfort has been shown by Siple and Bazett,[41] Spealman,[42] Clinton,[10] Folk and Peary,[13] Morris and Blair.[24,66] It was demonstrated in EPS Special Report No. 37,[13] that the amount of moisture accumulated under an impermeable barrier was modified by the thickness of the absorbent layer between the skin of the foot and the impermeable barrier.

The hypothesis was developed in that report that this phenomenon was due to the repenetration of relatively large quantities of sweat into the skin from which it had originated as perspiration, rather than suppression of sweat production.

The present investigation was designed to offer evidence on the problem of the use of impermeable footgear and the effect of an impermeable layer near the skin on the physiologic processes of the foot. The moisture and temperature relations of the clothed human foot are complicated. The foot is a point on the body which has frequent fluctuations in rate of blood flow in response to temperature changes. On the top of the foot thermal sweating alone appears, whereas on the sole "psychic" sweating appears in response to emotional stimuli.[7,8] A sweating foot is a problem even at very low environmental temperatures. In addition to the thermal and "psychic" types of glandular sweating, insensible moisture is given off by the entire foot. To these normal variations in moisture production by the foot are added the variations resulting from different types of footgear.

2. Evidence for the Reduction in Accumulation of Perspiration by an Impermeable Barrier

Details of the methods of application of an impermeable vinylite pistol cover over varying numbers of pairs of socks have been reported elsewhere.[13] With these methods it was demonstrated that accumulation of foot perspiration is appreciably less when the barrier is worn outside the innermost pair of three pairs of socks ("near" barrier) than when the barrier is worn outside the three pairs of socks ("far" barrier). The significant difference in accumulation of foot perspiration under the "near" and "far" barrier applies to insensible moisture from the entire foot, thermal sweat and non-thermal sweat. The justification for grouping these types of water loss under the term "perspiration" was presented in the earlier report.

The large difference between collections under "near" as compared with the "far" barriers was demonstrated in both field and laboratory tests in cool and warm environments. The laboratory tests in an air-conditioned room, also showed that the rate of accumulation of foot perspiration under an impermeable barrier decreases as soon as very small quantities of perspiration collect in the medium near the skin. The lessened accumulation of perspiration under the "near" barrier appears to be a local effect as indicated by a reduced accumulation under a "near" barrier which covers only the sole of the foot. Furthermore when the hands were dressed in "near" and "far" barriers about twice as much perspiration accumulated under the "far" barrier as under the "near".

Table I presents the procedure and data from a typical test taken from EPS Special Report No. 37.

TABLE I: COLLECTIONS OF TOTAL FOOT PERSPIRATION AS MEASURED BY WEIGHT GAIN OF SOCKS

Experiment A*

Subjects: S.G. and L.R.	Body Clothing: Heavy sweaters and flannel trousers
Environmental Conditions:	Field test
Duration:	8 hours
Footgear:	3 pairs of socks, shoepacs, a "near" barrier on left foot, a "far" barrier on right foot.
Activity:	Routine walking and 1 hour of moderate exercise
Test Procedure:	Both impermeable barriers were sealed to the skin above the socks by adhesive tape and collodion. A rubber tube was sealed into the system. All barriers were shown by inflation to be airtight during the experiment.

Results	Subject S.G. grams	Subject L.R. grams
Perspiration collected in Single Sock under "Near" Barrier (Left Foot)	14.9	9.5
Perspiration collected in Three Socks under "Far" Barrier (Right Foot)	42.8	20.2

* For further details see aforementioned EPS Special Report No. 37.[13]

The reduction in the accumulation of perspiration by a moisture proof barrier near the skin (Table I) is a typical example of one of the 92 experiments performed on 25 subjects. In all instances more perspiration accumulated under the "far" than under the "near" barrier, the smallest difference noted being a "far" barrier value 30 percent greater than the "near" barrier. In many cases the sweat accumulation in the socks under the "far" barrier was increased four- to fivefold.

Four possible mechanisms must be considered for the reduction in the accumulation of total perspiration under a "near" impermeable barrier. These may be: (1) suppression of production of insensible moisture and/or sweat; (2) repenetration and absorption of insensible moisture and sweat; (3) a combination of suppression and repenetration; and (4) some unknown mechanism.

A distinction is made in this report between the terms of penetration, repenetration, and absorption. By penetration is meant the passage of substances (fluid or solid) into and through the outer layers of the skin, presumably until the dermis is reached. Repenetration would apply to the penetration of substances (such as sweat) which were produced by the skin. The term absorption will be used in this paper to indicate the further continuance of the substance from the skin into the lymph or blood vessels.

In this report attempts are made to evaluate the effect of impermeable barriers upon sweating and upon insensible moisture loss through the skin. Once outside the skin the source of the water is no longer important.

No difference was noted in the sensations between the two feet under "near" and "far" barriers. This suggests, but does not prove, that differences in stimulation of sensory nerve endings in the foot under the "near" barrier are not responsible for a suppression of sweat gland activity. Sweat gland secretion pressures of 250 mm.Hg. have been reported[5] and the suppression of sweat glands by hydrostatic pressure from wet socks seems unlikely.

Some layers of the skin do imbibe water, but Bazett[3] discounted the possibility of penetration and absorption through the skin. In his studies on the effects of baths on men, he states:

> "There is no evidence of any water absorption through the skin. The subject gains slightly in weight during the first 30 minutes; this increase amounts only to about 50 to 100 grams, and is probably due to the skin becoming sodden."

If water penetrated into the living cells of the epidermis, under the conditions of our experiments this water could be carried off through the system of epidermal lymph channels[9,23] or by diffusion into the capillaries. The reference of Bazett to sodden skin presumably refers to the cornified epidermis and not the living cells of the epidermis. Osborne[27] considered the outer skin layers as a gel containing water of imbibition which could be increased over normal so that the layers would swell.

Calculations show that an increase of foot volume of the order of 75 cc. would be required to account for the apparent water absorption in the experiment detailed previously, and while actual measurement of foot volume was not made, no perceptible swelling was observed.

Presoaking of the feet with distilled water or with saline solution was employed as a method for ruling out any effect of imbibition upon the interpretation of the results obtained. Presoaking also reduced variability in the initial state of skin dryness. The usual difference between moisture accumulation under "near" and "far" barriers was observed whether the feet were presoaked or not, as indicated below.

TABLE II: EFFECT OF FOOT SOAKING IN 0.9% SALINE UPON THE COLLECTION OF PERSPIRATION IN SOCKS

Subject: R.P. Conditions: Field Test Duration: 8 Hours

Experimental Day	Pre-treatment	Grams Water Collected	
		Under "Near" Barrier	Under "Far" Barrier
1	No foot soaking	17.1	49.1
2	"Near" barrier foot - soaked for 30 minutes	16.2	53.0
3	Both feet - soaked for 30 minutes	14.4	54.9

As a further check upon the magnitude of the imbibition effect for use in interpreting the experimental results, the amount of water which could be imbibed by dry peelings of epidermis was determined. Five samples of peelings of epidermis from the foot were dried over calcium chloride, and then soaked in water. They gained an average of 112.4 percent in weight (92 to 147 percent). Using this average value and an average foot area value, the epidermis of the foot can be estimated to hold somewhere between 10 and 30 grams of water. While the magnitude of apparent repenetration is in many instances larger than this, care was taken to soak both feet before beginning the experiments, except when chloride measurements were made or special exceptions were made as noted. The experiments reported here were designed to evaluate the alternative hypotheses of suppression and repenetration of sweat and insensible moisture.

3. Materials and Methods

a. Subjects

The test subjects used were 52 college students aged 18 to 28 years and two investigators aged 35 and 45. No subject was used if preliminary study indicated a difference in sweating of the right and left foot. Most experiments were carried out in an air-conditioned room which was maintained at 80°F., 50 percent relative humidity, and with slightly turbulent air. A variety of other experiments were performed which included subjects exercising in a gymnasium, a prolonged study on several students who continued their normal daily routine for eight hours, and a two-day field test which included a mountain climb by eleven subjects. These experiments involving activity are referred to in this report as "Field Tests". All experiments were conducted in the fall, winter, or early spring when thermal sweating was easier to control.

In the air-conditioned chamber the subjects wore light standard body clothing of either flannel trousers and T-shirt, or shorts only. Clothing and footgear were conditioned at 80°F. and 50 percent relative humidity for 20 to 24 hours before use. The subjects remained in a sitting position with both feet on the floor. To minimize any effect of food ingestion upon vasomotor function and non-thermal sweating, all measurements were begun 90 minutes or more after a meal. Activity was minimal; the metabolic rate for the subject most intensively studied was 49.3 Calories per square meter of body surface per hour when experiments in the air-conditioned chamber were in progress.

Each subject was prepared as follows: the urinary bladder was emptied and 750 cc. of tap water was ingested. If chloride analyses were not part of the experiment the feet were soaked for 30 minutes in normal saline and five thermocouples were fastened to each foot with adhesive tape. Under the conditions described for these experiments it may be assumed that the toes were vasodilated and the secretion of thermal sweat was light to moderate.

Because of the day-to-day intra- and inter-individual differences, the method of control employed in these experiments was to compare on any one day, the difference between right and left foot of each individual with each different experimental combination of footgear. Control experiments previously reported[13] support the validity of this method.

To determine whether the presence or absence of a barrier had an important effect upon the foot sweating of the contralateral foot the following experiment was carried out. A barrier was worn on one foot (index foot) every day, and on alternate days a similar barrier was worn on the opposite foot. The average values for sweat collected with and without a barrier on the contralateral foot are indicated below.

TABLE III: EFFECT OF BARRIER ON CONTRALATERAL FOOT ON SWEAT PRODUCTION

Sweat Collection on Index Foot		
Group	Without Contralateral Barrier	With Contralateral Barrier
1 (6 men)	14.7 grams	14.2 grams
2 (14 men)	12.4 grams	11.9 grams

Analysès of this data by "t" test showed that the amount of perspiration collected from the index foot was not influenced by the presence or absence of a barrier on the opposite foot. In Group 1, "t" = 0.77, and in Group 2, "t" = 1.02, indicating that the differences observed might arise through chance alone 50 percent of the time.

b. Perspiration Collection Methods

The standardized footgear combinations used in collecting perspiration for the initial experiments which demonstrated the reduction in accumulation of perspiration by an impermeable barrier near the skin are given below.

TABLE IV: FOOTGEAR COMBINATIONS

Layer No.	"Near" Barrier Foot	"Far" Barrier Foot
1	Light wool sock (Cushion Sole)	Light wool sock
2	Impermeable barrier	Heavy wool sock
3	Heavy wool sock	Heavy wool sock
4	Heavy wool sock	Impermeable barrier
5	Shoepac	Shoepac

The impermeable barriers were vinylite pistol covers of rectangular shape. They were easier to fit than rubber socks and were equally comfortable. The vapor barrier was fastened at the top by means of a heavy elastic band which held the top tight against the skin. An experiment comparing the effect of sealing the top with waterproof adhesive tape to fastening with an elastic band showed that the maximum error due to escape of moisture around the elastic band was 0.1 to 0.4 gram (see Appendix A). The footgear assembly used provided heavy insulation for the ambient air conditions encountered in these experiments, but it was needed as a device to keep the barrier near the skin on one foot and away from the skin on the other. The subjects were comfortable when dressed in light body clothing and this footgear. Data were not obtained with skin temperatures below about 74°F.

A special device, consisting of a copper boot shaped roughly like a foot into which a foot could be sealed with rubber dam material, was used to collect sweat in some of the experiments. The space between the foot and the inside of the copper boot contained (1) saturated still air, or (2) water, or (3) a current of dry air moving at 65 cubic meters per minute.

When either saturated "still" air or water was the medium in the copper boot, perspiration gain into the boot was measured by weighing it with an accuracy of ± 2 grams. When a stream of dry air was passed over the foot, perspiration from the foot was collected in copper tubing immersed in an alcohol and dry-ice bath. This technique, modified by Neumann,[26] was tested with wet sock material placed in the copper boot to simulate a foot. Quantities of water varying from 10 to 40 grams lost from sock material were recovered in the coils with an average error of ± 0.6 gram and a maximum error of +2.2 grams. In all copper boot experiments the immediate environment outside the boot was thermostatically controlled so that the skin temperature of both feet was approximately the same. In most cases average thermocouple readings of both feet checked within 1°F. These temperatures were measured by a Leeds and Northrup Millivolt Indicator with a limit of error of ±0.5°F.

In some experiments the perspiration collected under an impermeable barrier outside three socks was compared with that collected under a barrier placed over one, two, four, or five socks. Periodic checks of the moisture adhering to the skin after socks were removed showed negligible amounts except when the feet had been in the copper boot containing water or saturated air. Only in the tests with the copper boot was a significant amount of skin moisture picked up on the towels used to dry the feet.

c. Chloride Analyses

The occurrence of repenetration under the "near" barrier could be established by evidence that sweating continued at its normal rate. Chloride analysis of perspiration collected in the socks was used as a measure of sweating.[19,20] Before each experiment the socks were washed with successive volumes of distilled water until the wash water was practically chloride-free as determined by measurement of electrical resistance between two fixed platimum electrodes immersed in the water (the same set of electrodes was used throughout). It was found that a measured resistance of 600 ohms corresponded to a chloride concentration no greater than 0.2 mg. per liter. Sweat chloride which had accumulated during experiments was similarly washed out of the socks using the same "end point" (600 ohms) as a measure of complete chloride extraction. The washings were combined and diluted to the nearest liter in volumetric flasks. Chloride analysis was performed in triplicate by Keys'[17] modification of the Volhard method, using 50 cc. aliquots. With known quantities of chloride added to socks, values of 3 to 4 mg. per sock were recovered with an accuracy of ± 17 percent, values of 20 to 30 mg. per sock were recovered with an accuracy of ± 4 percent, and values of 50 to 80 mg. with an accuracy of ± 3 percent. Unless otherwise stated during experiments involving chloride analyses, the feet were not presoaked but instead were washed, inspected for cleanness, and rinsed with distilled water to reduce any possible accumulation of chloride on the skin. Before use in an experiment, the fresh socks, cloth towels, paper towels, and copper receptables were determined to have a very small blank chloride content.

The preliminary foot soaking used in previous experiments was useful not only for saturating the cornified epidermis, but to equalize the effects of temperature and exercise on subjects before the experiments by bringing skin temperature to a stable starting point. This element of control was sacrificed in experiments in which chloride analyses were to be done because it was not known how a bath of distilled water would affect the composition of the sweat produced. A saline bath might also cause contamination of the socks. The decision to omit preliminary foot soaking when chloride analyses were to be done was based upon the control tests which showed that moisture production was about the same with and without soaking in normal saline. These data are presented below.

TABLE V: PERSPIRATION COLLECTED IN GRAMS

Footgear: "Near" barrier on both feet
Conditions: Field test
Duration: Eight hours
L: Left Foot. R: Right Foot

Experimental Day	Subject	Foot Soaked in Saline for One Hour Before Experiment	Foot not Soaked
1	N.O.	9.1 grams L	9.5 grams R
1	H.P.	13.0 grams L	15.4 grams R
2	N.O.	7.1 grams R	7.5 grams L
2	H.P.	25.3 grams R	23.3 grams L

d. Vapor Pressure Measurements

Vapor pressure was measured with a thermoelectric psychrometer in the three sock layers worn under an impermeable barrier and next to one sock worn under an impermeable barrier (see Figure 1). These psychrometers were developed and constructed using basic principles reported from the Quartermaster Climatic Research Laboratory in Report No. 81.[45] The frame was a piece of plexiglass 1/8 inch thick, 1-1/4 inches long and 15/16 inch wide. Two parallel slots, 1/4 inch wide and one inch long cut lengthwise in the frame contained wet and dry thermocouples. Thermocouples were of 0.005 inch diameter copper and constantan wire, butt welded. "Spaghetti" type insulation was cemented into the frame and extended for six inches on all four wires. This prevented the thermal interference which occurred when a common constantan lead was tried. The wet thermocouple was wrapped in fibers scraped from a thread of standard wet-bulb wick and was kept wet from a small reservoir drilled in the plastic frame. Consistent readings without air circulation were not obtailed until the diameter of the wick-wrapped thermocouple was less than 0.01 in. The use of covers made of plastic mesh (fly screen) resulted in uniform values when the socks were wetted with widely varying quantities of either sweat or distilled water (see Appendix B). Four such instruments gave nearly the same readings (±1.0 percent RH) during calibration between 81 percent and 97 percent relative humidity. A sample calibration is shown below.

THERMO-ELECTRIC PSYCHROMETER

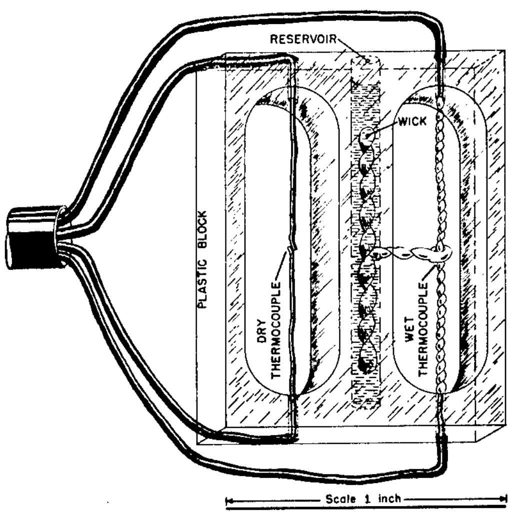

FIGURE 1

TABLE VI: PSYCHROMETER CALIBRATION

	Relative Humidity		
Hg Sling Psychrometer	81%	90%	97%
Psychrometer No. 1	82.5	92	97
Psychrometer No. 2	82.5	93	97
Psychrometer No. 3	80.5	93	98
Psychrometer No. 4	82.5	92	97

The thermoelectric psychrometers gave higher humidity values than did the mercury type psychrometers. Each psychrometer was calibrated before and after each experiment. The maximum error for all psychrometers was determined from a plot of 60 calibration values for each psychrometer. The error was ±5.5 percent which expressed in vapor pressure near skin temperature is a possible error of ± 2.46 mm. Hg.

Relative humidity measurements from the capsule psychrometers were converted to vapor pressure, and the dry bulb temperature of the appropriate capsule was read from a chart of vapor pressure readings for distilled water. Vapor pressure of tissue was calculated from skin temperature measured by thermocouples taped to the skin adjacent to the innermost capsules. A table of tissue vapor pressure was made by interpolation between Pinson's figures[66] of 24 mm. of mercury at 26°C. and 43 mm. mercury at 36°C. From these two points a calibration curve was drawn to approximate the shape of the curve for water vapor in the same temperature range. These data are shown in Appendix D.

4. Results

a. Penetration of Water from Pre-Wet Socks

Fluid, consisting of distilled water, perspiration, or various sodium chloride solutions was distributed in a single inner sock under an impermeable barrier at the start of these experiments. The experiments included 40 conducted in the air-conditioned chamber with ten subjects studied over a two-hour period, and 27 field tests of ten hours each on five subjects. In some experiments feet were immersed in the copper boot. The data from the air-conditioned chamber experiments with the subjects seated are presented in Table VII.

When the quantity of water used to pre-wet the socks approximated the quantity of sweat collected in a single sock during one hour of vigorous exercise, some subjects showed penetration of water into the skin while others did not. Apparently there is a particular equilibrium value for wet socks for each individual. A series of these values, varying from 16 cc. to 30 cc. has been reported.[13] A similar variability in equilibrium values and apparent penetration was found in the present series, as follows: (1) Subjects R.P. and S.P., with socks pre-wet with 19 to 28 cc. of water, consistently showed no apparent penetration, but there was a perspiration contribution to the socks varying from 0.1 cc. to 4.4 cc. in two hours. (2) Three subjects with 27 cc. of water in their socks showed an apparent penetration varying from 0.0 to 4.1 cc. in two hours. (3) Three different subjects were tested with large quantities of moisture in contact with the skin. Either 47 cc. of moisture was applied in socks, or the feet were immersed in seven liters of distilled water. In these experiments the apparent penetration was 0.6 cc. to 2.7 cc. in two hours or up to 2.2 grams in three hours. (Table VIII).

TABLE VII: PENETRATION OF WATER FROM SOCKS INTO THE FOOT

Figures out of parentheses are the amounts of fluid in socks at start of each experiment. Figures in parentheses show amount of fluid gained by socks from perspiration (plus values) or lost by penetration (minus values)

Preparation: Feet soaked for one hour in 0.9 percent Saline.
Duration of Experiment: Two hours.
Conditions: Sitting in air-conditioned chamber.
"Near" barrier on both feet.
L: Left Foot R: Right Foot

Subject	R.P.		S.B.		S.P.		A.B.		O.B.		O.B.		G.Y.		O.S.	
	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
Fluid Used Distilled H_2O	24 (+1.1)	21 (+1.7)	20 (+3.0)	19 (+4.4)	27 (+2.6)	27 (+1.4)	47 (-1.7)	47 (-1.8)	27 (-2.3) 27 (-2.4)	27 (-2.2) 27 (-1.9)	27 (-3.0)	27 (-3.7)	27 (-3.6)	27 (-3.3)	27 (+3.2)	27 (+2.8)
Perspiration	24 (+1.4)	21 (+1.3)	20 (+2.5)	19 (+3.1)	28 (+1.6)	28 (+0.1)	48 (-2.1)	48 (-1.9)								
0.2 percent Saline	24 (+2.5)	21 (+3.3)	20 (+2.6)	19 (+3.3)	27 (+1.9)	27 (+2.4)	47 (-2.7)	47 (-1.0)								
0.45 percent Saline									27 (-2.2)	27 (-2.3)	27 (-3.2)	27 (-3.2)	27 (-3.6)	27 (-3.3)		
0.9 percent Saline	24 (+2.3) 24 (+0.5) 24 (+3.3)	21 (+1.5) 21 (+1.8) 21 (+3.4)	20 (+2.1) 20 (+2.8)	19 (+2.9) 19 (+3.4)	27 (+2.7)	27 (+2.2)	47 (-2.3)	47 (-1.3)	27 (-1.9)	27 (-1.4)	27 (-2.7)	27 (-3.2)	27 (-2.6)	27 (-2.6)		
2.0 percent Saline					27 (+2.5)	27 (+3.2)	47 (-1.0)	47 (-0.6)	27 (-2.6)	27 (-1.3)	27 (-2.4) 27 (-1.5)	27 (-2.2) 27 (-3.1)	27 (-3.2)	27 (-2.8)		
5.0 percent Saline									27 (-2.0)	27 (+0.2)	27 (-2.2)	27 (-3.3)	27 (-4.1)	27 (-2.5)		

TABLE VIII: WATER ACCUMULATION OR PENETRATION AND CHLORIDE ACCUMULATION COMPARED IN SOCKS APPLIED DRY AND WET
Conditions: Field tests of ten hours each day.

WATER AND CHLORIDE EXCHANGES OF FOOT IN A WATER BATH THREE HOURS A DAY COMPARED TO THREE DRY SOCKS

Subject	AB		NO		NO		NO*		RW		HP		DJ	
Number of Days	5		5		6		6		6		3		3	
	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry
Mean Daily Loss or Gain of Water (Grams)	-12.1	+10.9	-14.7	+10.8	-6.6	+11.0	-2.6	+11.9	-5.7	+16.6	-1.4	+15.6	-0.4	+14.0
Range	(-9.6 to -17.1)	(+9.6 to +12.6)	(-8.9 to -22.3)	(+7.8 to +15.0)	(-2.6 to -8.2)	(+6.9 to +16.2)	(-1.5 to -3.9)	(+7.8 to +16.6)	(+0.8 to -11.5)	(+8.6 to +25.1)	(-1.4 to -1.5)	(+13.4 to +18.1)	(+1.7 to -2.2)	(+10.8 to +16.7)
Total Chloride (mg.)	126.4	126.4	73.9	73.9	86.6	75.4	82.4	75.6	155.9	162.9	100.6	61.4	46.4	56.9
Mean Chloride Per Day (mg.)	25.3	25.3	14.8	14.8	14.4	12.6	13.7	12.6	26.0	27.2	33.5	20.5	15.5	19.0

*27 grams instead of 50 added each day

In these experiments on sitting subjects with presoaked socks each subject tested the effects of distilled water, 0.2 percent or 0.45 percent saline, 0.9 percent saline; and 2.0 percent or 5.0 percent saline (Table VII). These experiments failed to establish any clear-cut influence of sodium chloride concentration upon the penetration phenomenon.

Penetration experiments were also done in ten-hour field tests. The results in Table VIII show the mean decrease from the 50 grams of water placed in the socks at the start of each test day. Losses up to 22 grams of water were observed. Only one of these tests failed to show an appreciable change.

Four additional field tests were run on two subjects wearing socks soaked with 90 cc. of distilled water. These socks were worn under an impermeable barrier sealed to the skin with adhesive tape for ten hours. As shown in Table IX, as much as 37 cc. of water had penetrated the skin by the end of the experimental period.

TABLE IX: DECREASE IN WATER CONTENT OF SOCKS CONTAINING 90 GRAMS AT START OF EXPERIMENT

Subject	Left Foot	Right Foot
S.P.	33.0	--
O.B.	29.5	34.2
O.B.	18.0	37.6
O.B.	--	22.6

These studies showed a measured penetration of approximately 1 cc. of water per hour into the feet of seated subjects, and a measured penetration of 2 cc. to 3 cc. per hour for eight or ten hours when the subjects walked part of the time. It was supposed that this measured penetration represented only one component of the actual amount of fluid that had been removed from the socks. The remainder, to be referred to as the calculated penetration, would originate from continuous sweating which would supposedly increase the fluid content of wet socks unless repenetration occurred.

b. Evidence that Sweating Continues at its Normal Rate under a Near Barrier

Evidence of continued sweating under near barriers was obtained by three methods. In one series of field tests the subjects each day wore a sock which was initially dry on one foot and a sock initially wet on the other foot. Each day's experiment lasted for ten hours. (Table VIII). If external water could suppress sweat gland activity, the wet sock should prevent secretion and appreciable chloride would not be expected in the sock at the end of the experiment. In a second series a near barrier was worn on one foot and a far barrier on the other for three days in the field (Table X). If the near barrier suppressed sweating there should be far less sweat chloride accumulated under the near barrier than under the far barrier at the end of the three-day period. In a third variation, sweat was collected from seated subjects with one foot immersed in water and the other foot dressed in three socks (Table VIII).

The amount of sweat chloride collected in one day was too small to measure accurately. For the experiments reported in Table VIII the subject wore the same pair of socks during the experimental period of five to six days. The wet socks were retreated to contain 50 cc. of water at the start of each day, with the exception noted where 27 cc. of water was used. The wet socks lost weight during the daily period of wear in nearly all cases. The sock on the opposite foot was dry at the start of each day. It is significant that 20 minutes after the wet and dry socks were donned each morning, the subject frequently could not detect a difference in sensation of wetness between the two feet.

As a control measure subjects N.O. and R.W. shown in Table VIII alternated the wet and the dry sock from foot to foot each day. The overall results indicate that sweat chloride was approximately the same on both feet, which is interpreted as indicating sweat rates of comparable magnitude into wet and into dry socks.

In the second series (Table X) including prolonged and continuous wear of a near and a far barrier, it was advantageous to simulate the accumulation of an extra day's moisture. When the footgear was donned 10 grams of distilled water were placed in the sock under the near barrier and 35 grams in the three socks under the far barrier (Table X). This preliminary wetting was supplemented by an accumulation of perspiration which showed the usual reduction in accumulation under the far barrier. In one case there were four times and in the other cases at least six times as much water or perspiration under the far barrier as under the near barrier. The socks under the near barrier showed an extraordinarily high content of chloride. These values were from 50 percent to 122 percent of the chloride in the three socks under the far barrier. These results can only be explained in terms of a relatively normal rate of sweating under the near barrier, or a discrepancy of improbable magnitude in the chloride concentration of sweat secreted by opposite feet. This, taken together with the first series, must be considered as strong evidence that repenetration does occur under the near barrier.

Three of the four subjects taking strenuous exercise were found to have more chloride under the far barrier than under the near barrier. It is not known from these experiments whether this represents partial suppression of sweat under a near barrier, a repenetration of

TABLE X: CHLORIDE CONTENT OF SOCKS WORN DURING STRENUOUS EXERCISE

Values for Each Sock Represent Milligrams of Chloride

Conditions: Field Test - Including Mountain Climb
Duration: Continuous Wear for Seventy-two Hours
Near: Content in Sock Under Near Barrier
Far: Content in Sock Under Far Barrier

Subject	E.F.		R.P.		P.H.		O.B.	
Barrier	Near	Far	Near	Far	Near	Far	Near	Far
Inner Sock	77.7	140.2	98.4	86.8	57.2	82.7	119.9	71.9
1st Ski Sock		29.0		31.7		32.9		15.3
2nd Ski Sock		15.8		7.6		8.6		10.3
Total	77.7	185.0	98.4	126.1	57.2	124.2	119.9	97.5
Total Perspiration Collection in Grams	-0.6	50.0	22.6	88.7	12.5	76.9	11.9	68.6
Strength of Perspiration Collected (Percent Chloride)		0.37	0.43	0.14	0.46	0.15	0.23	0.14

chloride as well as water, or an effect of exercise upon the chloride concentration of sweat secreted under the near barrier.

Sweat chloride accumulated in the foot bath was compared to that accumulated in socks as reported in Tables VIII and X. Sweat was collected while one foot of each subject was immersed in seven liters of distilled water and the other foot was dressed in three socks. The foot-soaking bath was used to study possible suppression of sweat glands by hydrostatic pressure. Chloride was allowed to accumulate in each foot-soaking bath during three experiments on three consecutive days. The perspiration collection in socks and the chloride content of the sock perspiration and of the foot baths are presented in Table XI.

TABLE XI: COMPARISON OF SWEAT AND CHLORIDE ACCUMULATED IN SOCKS AND FOOT BATH

Subject	H.P.		D.J.	
Day	Foot Bath	Socks	Foot Bath	Socks
	Left Foot	Right Foot	Left Foot	Right Foot
		cc.		cc.
No. 1		15.2		16.7
No. 2		18.1		14.6
No. 3		13.4		10.8
Total Perspiration		46.7		42.1
Chloride Collected in mg.	100.6	61.4	46.4	56.9

As indicated by chloride output, approximately equal amounts of sweat were contributed to the foot bath and to the socks. The high foot bath value of chloride for subject H.P. is unexplained since the foot bath increased in chloride concentration but not appreciably in volume. With both subjects fluid equal to the sweat produced must have repenetrated into the skin.

The observations that sweat chlorides were collected in similar quantities: (1) in both wet and dry socks; (2) under near and far barriers; and (3) in a water bath compared with a sock control, provide presumptive evidence that sweating continues at normal rates under near barriers. Therefore it is believed that repenetration of water must account for most of the difference in thermal and non-thermal sweat accumulation under near and far barriers. Insensible moisture in footgear must be considered separately since this contribution to total perspiration does not contain chlorides. Suppression of insensible moisture can only occur if the vapor pressure outside the skin approaches that in tissue fluid inside the skin. Accordingly, to study these relationships a series of measurements were made of vapor pressure next to the skin of the foot under near and far barriers, and in sock layers with varying degrees of moisture in socks.

c. Vapor Pressure Measurements to Investigate Possible Suppression of Insensible Moisture

In practice, vapor pressure measurements were made between the skin and inner socks containing moisture varying from 0 to 13 grams. This range simulates up to eight hours of insensible moisture accumulation, which amounts to 1.0 to 2.0 grams per foot per hour. These values of 1.0 to 2.0 grams per hour were obtained from experiments cited in an earlier report[26] and from far barrier values obtained in a new series of eight experiments on two subjects (see Appendix C).

The technical difficulties of development and use of the thermoelectric psychrometers were such that the data were obtained from an intensive series of observations on only one subject, supplemented by experiments on a second subject. Approximately 250 measurements were made on each of four psychrometers used simultaneously. The readings were made at half-hour intervals during the forty experiments which lasted either three or eight hours. These experiments were designed to measure vapor pressure: first, at five different locations on the skin inside of the sock under a near barrier; and second, between all layers in both near and far barrier combinations with variable quantities of water in the socks (see Appendix E).

Vapor pressure values for water were calculated from the readings of relative humidity, and estimated in terms of differences from tissue fluid to outer skin surface, and from sock layer to sock layer. Most measurements tabulated represent averages of the last two readings of each experiment. In determining the vapor pressure differences from tissue fluid to outer skin surface, values for vapor pressure in skin tissue as cited by Pinson[30] were used as described under paragraph 3, Materials and Methods.

The studies of vapor pressure at five different locations on the surface of the foot formed the basis for selecting the center of the sole and the center of the dorsum for more intensive observations as index values for the entire foot. The data from five locations are presented in Appendix F. As indicated by these values the dorsum usually represented a damper section than the sole, when total quantities of perspiration in socks varied from 0 to 11 grams (see also Appendix E).

The studies of vapor pressure near the skin surface and between sock layers confirmed the view, as noted by Belding,[4] that vapor pressure in clothing worn at room temperature or lower usually decreases with the distance from the skin. Illustrations of this phenomenon are given in Figures 2 and 3. In all cases with the far barrier a vapor pressure difference of approximately 10 mm. of Hg. was calculated from skin tissues to barrier (Appendix G), while in near barrier experiments the difference was less and was occasionally reversed with a slightly higher vapor pressure next to the barrier (outside the sock) compared to the pressure next to the skin (inside the sock). The vapor pressure differences under the far barrier plus unstudied factors such as temperature and different weights of socks, frequently caused a ratio of moisture distribution in the three socks on each foot of approximately 1:2:4. This ratio held for variable quantities of water in socks.[13] Typical examples of such moisture relations are illustrated in Figures 2 and 3.

CHANGES IN VAPOR PRESSURE AS MOISTURE IN SOCKS INCREASED DURING A FOUR-HOUR EXPERIMENT
(SUBJECT R.P.)

CROSS-HATCHED BARS REPRESENT GRAMS OF PERSPIRATION OR DISTILLED WATER IN SOCKS

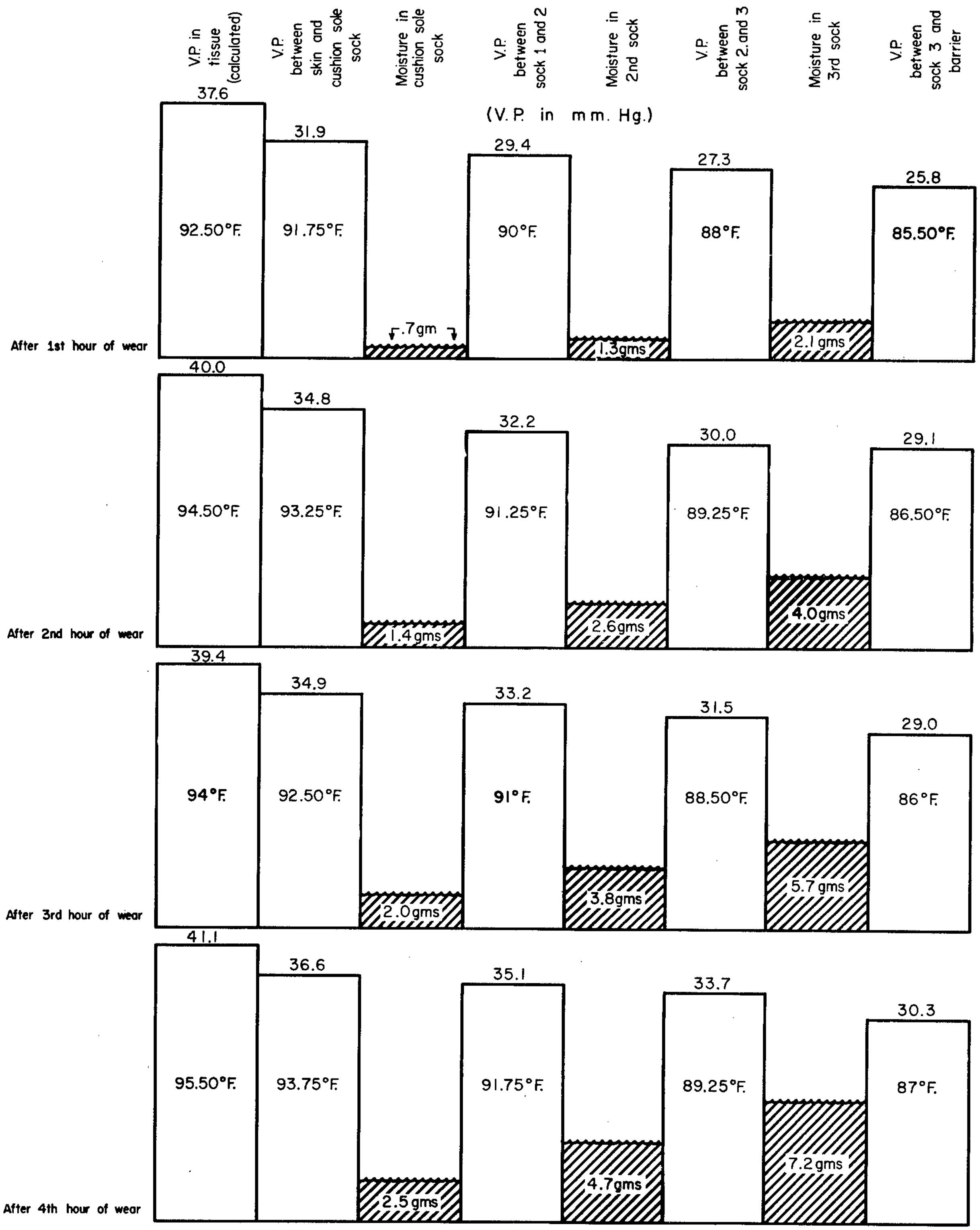

FIGURE 2

VAPOR PRESSURE MEASUREMENTS WITH DIFFERENT QUANTITIES OF MOISTURE IN SOCKGEAR UNDER A "FAR" BARRIER

(SUBJECT R.P.)

SIMULTANEOUS READING BETWEEN LAYERS ON THE SOLE; CROSS-HATCHED BARS REPRESENT GRAMS OF PERSPIRATION OR DISTILLED WATER IN SOCKS

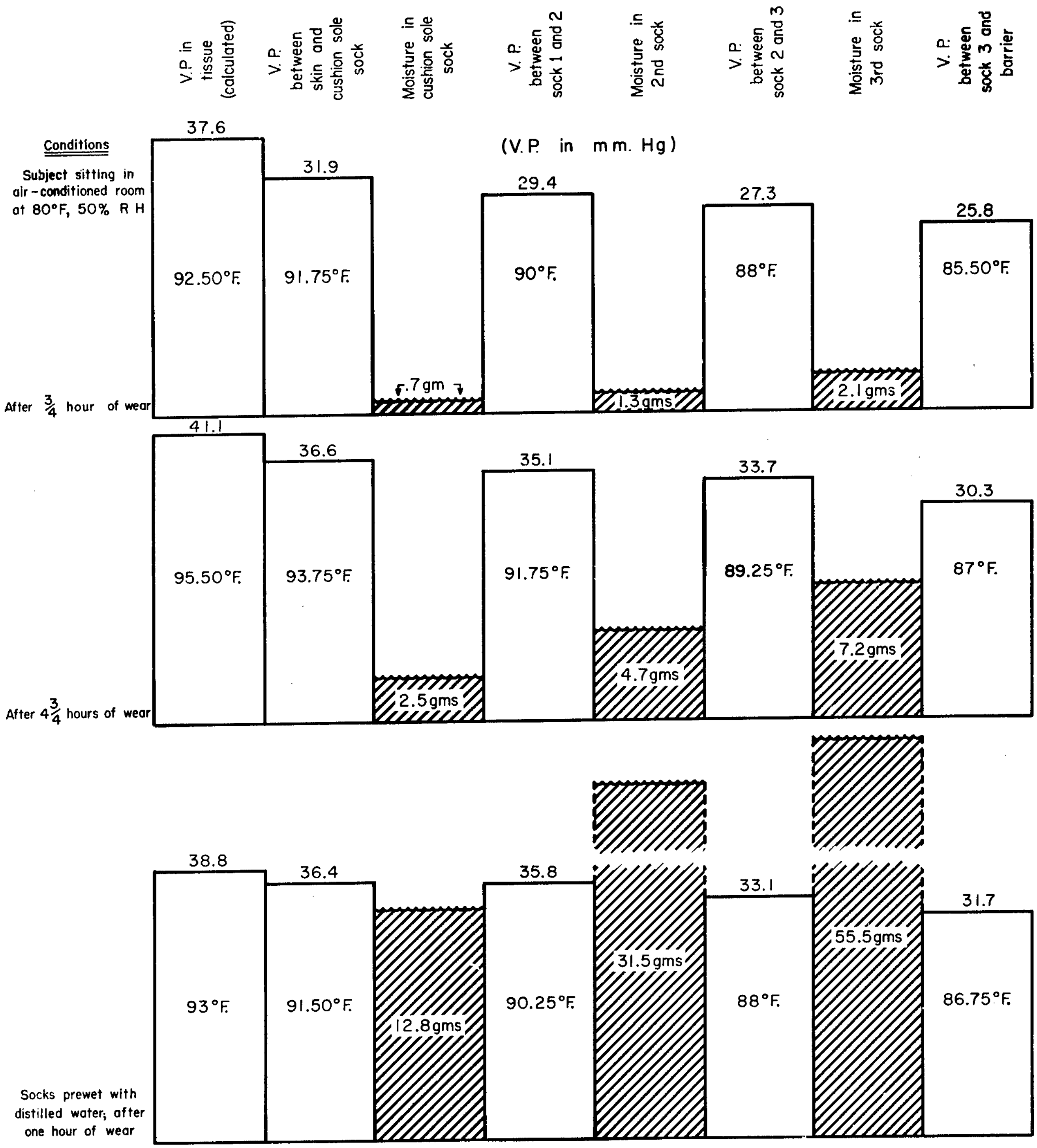

FIGURE 3

Of primary interest was the vapor pressure of the layer between skin and first sock. If this were equal to, or greater than, that of tissue fluid, the production of insensible moisture would be suppressed. The data from both subjects for measurements between the skin and first sock are included in Appendices C, E, and F. The differences between the measured values outside the skin and the values for tissue at different temperatures calculated from Pinson's values showed the following frequency distribution in a total of 59 measurements:

Differences in mm. Hg.	Frequency
-1.2 to 0.0	5
0.1 to 1.4	5
1.5 to 2.4	15
2.5 and over	34

The possible experimental error is about 2.5 mm. of mercury. The negative values (measured in one short series only, - see Appendix F) may represent error or a higher vapor pressure outside the skin than in tissue fluid so that moisture vapor would diffuse inward. The relation between water content of the inner sock and the vapor pressure (calculated as difference between measured vapor pressure between skin and first sock, and tissue fluid pressure at the temperature) are shown in the following examples:

Subject: R.P.

Location: Sole (Ball of Foot)

Grams of Water in Inner Sock	Vapor Pressure Difference in mm. Hg.		Skin Temperature °F.
	Under Far Barrier	Under Near Barrier	
0.7	5.7		92.5
1.1		4.4	91.0
1.4	5.2		94.5
2.0	4.5		94.0
2.1		3.2	90.0
2.5	4.5		95.5
3.4		3.5	90.0
4.8		5.1	94.5
11.4		2.6	94.0
12.8	2.3		93.0

As a generality based on all data collected, it may be stated that the measured vapor pressure in socks under both a near and far barrier was in nearly all cases lower than the calculated vapor pressure in the associated skin tissue. Apparently with this footgear a suppression effect on the diffusion of insensible moisture does not usually occur, but the rate of production of insensible moisture probably is lowered as moisture accumulates in the inner sock under both the near and far barrier. This rate would be lowered more rapidly under the near barrier.

d. Summary of Observations on Apparent Reabsorption of Perspiration

The experiments described in this report were designed to explain why up to five times as much moisture accumulates under a far barrier as under a near vapor barrier. The evidence that this phenomenon depends upon repenetration of water rather than suppression of sweat production and insensible moisture, is based upon observed penetration into the skin of externally-applied water, the demonstration by chloride secretion that approximately normal sweating continues under the near barrier, and vapor pressure measurements. This means that when water is applied externally to the skin under a near barrier the actual total amount of water which penetrates consists of part of this externally applied water plus much of the sweat which would evaporate from the foot if no barrier or sockgear were present. Thus the relationships under the near barrier are such that water in the sock, whether it originates from external sources, by accumulation from sweat glands, or as insensible moisture, comes to an equilibrium value in a few hours, apparently due to repenetration.

A separate series of experiments showed that the sweat collected under a far barrier (in three socks) can be considered only an approximate index of the calculated penetration of sweat under the near barrier (Table XII). This index is a minimal value for repenetration since the three socks under the far barrier do not collect all the perspiration from the foot, as indicated by the greater collection in five socks under a barrier than in three socks under a barrier. As shown in Figure 4 there is a progressively greater total accumulation with a greater number of socks under the barrier. Extrapolation of the line in Figure 4 suggests that the same phenomenon continues with more than five socks, and comparison of the values obtained in socks with those from the bare foot as obtained in the copper boot experiments, also suggest that some degree of repenetration occurs under five socks. This implies that the repenetration is not a new phenomenon related to impermeable footgear but occurs to some extent under leather and other permeable footgear.

Apparently repenetration for several days does not alter the performance or comfort of the human foot. In one test eleven men wearing near and far barriers and shoepacs completed a strenuous mountain climb without appreciable discomfort. The impermeable barriers worn by some of the men for 48 hours prior to the climb had caused continuous repenetration during this period. (The rest of the group had worn near and far barriers for 18 hours before starting the mountain climb.)

TABLE XII: COLLECTION OF PERSPIRATION WITH A BARRIER WORN OVER A VARIABLE NUMBER OF SOCKS

Duration: 3 Hours --- 80°F. --- 50% Relative Humidity

Number of Socks on Right Foot Under Barrier	R.Y.			R.S.			H.P.			J.J.			Average of Percents
	Left Foot Grams	Right Foot Grams	% Right of Left	Left Foot Grams	Right Foot Grams	% Right of Left	Left Foot Grams	Right Foot Grams	% Right of Left	Left Foot Grams	Right Foot Grams	% Right of Left	
One	11.7	6.1	52.1	13.5	6.0	44.5	15.1	6.3	41.7	13.2	5.3	40.1	44.6
Two	9.1	7.6	83.5	17.2	12.1	70.4	18.6	15.1	86.2	14.3	11.9	83.4	80.9
Three	9.4	9.8	104.0	12.1	12.2	99.2	16.2	15.9	98.2	14.0	14.3	102.0	100.85
Four	10.4	11.2	108.0	13.7	14.7	107.0	14.5	17.3	119.0	14.4	15.4	107.0	110.0
Five	10.3	12.7	123.0	12.9	16.0	124.0	16.6	21.6	130.0	14.7	18.1	123.0	125.0
Copper Boot	9.8	15.3	156.0	11.4	16.7	147.0	12.5	20.5	164.0	(13.0	22.6)		166.0
										(13.0	22.6)		

Note:

(1) "T"-Shirt and Light Trousers; Five socks on each foot at all times except when dry air was passed over the right foot; left foot always had barrier over three socks; no boots; rubber band held barriers to skin.

(2) Dry air was passed over the foot in the copper boot for three hours. Moisture from the foot was then condensed in coils in a dry ice bath.

(3) Skin temperatures were between 93° and 97°F. during these determinations.

EFFECT OF NUMBER OF SOCKS UNDER BARRIER UPON SWEAT COLLECTION

CONDITIONS: 5 SOCKS ON EACH FOOT — BARRIER OVER 3 ON LEFT, AND VARIABLE NUMBER ON RIGHT. 3 HOURS AT 80°F.

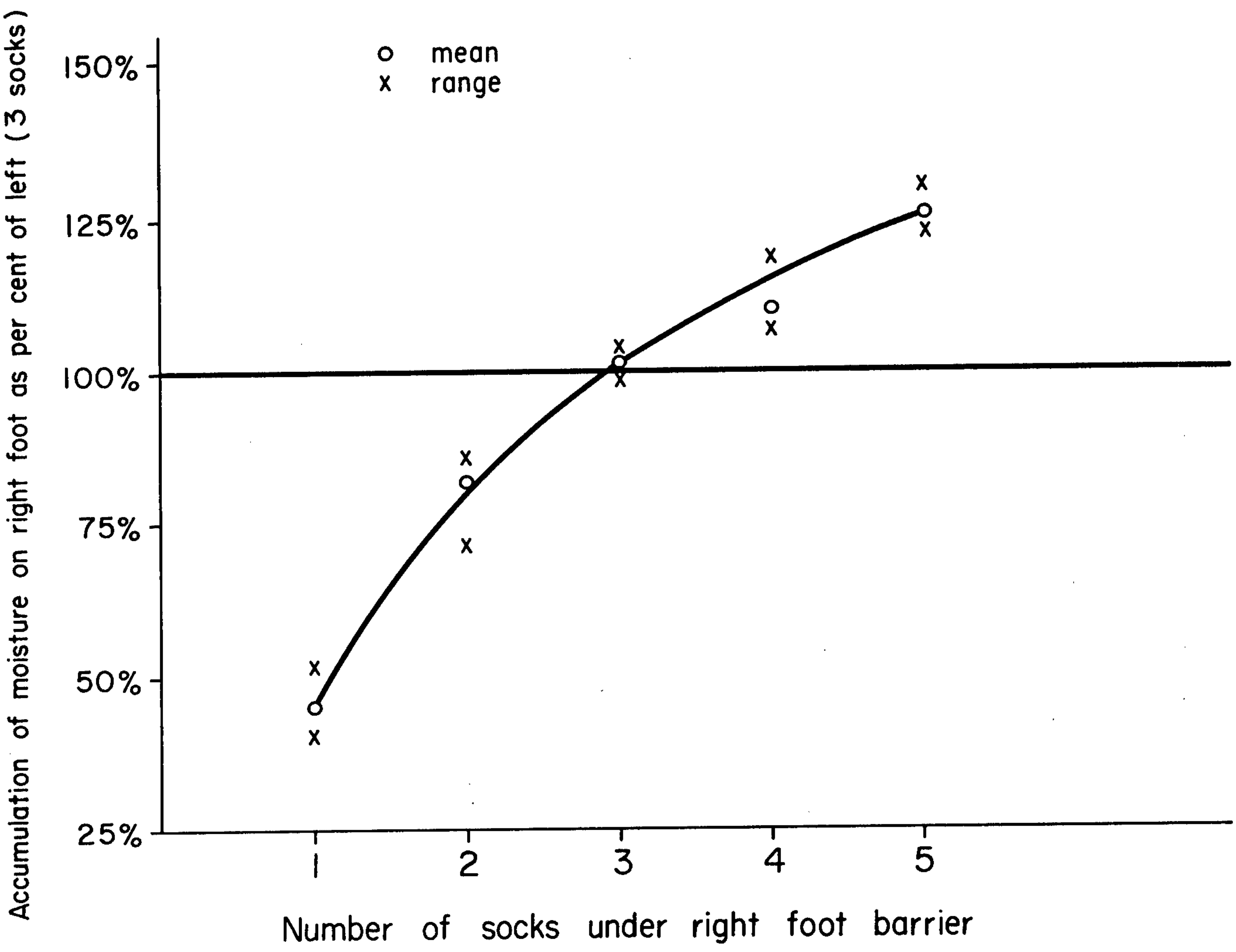

FIGURE 4

5. Discussion

In the present work the penetration of water into and through the skin of the human foot has been demonstrated. The pathway of this penetration and the composition of the penetrant should be considered. A marked division of opinion exists in the literature as to whether water penetrates human skin.[11,12,16,21,22,47] Most authorities agree that the keratin or horny matrix of the epidermis is impermeable to liquid water applied externally. The disagreement is concerned with possible penetration through follicular and glandular pores. Three authors (Rothman, Harry, and Calvery,[36,37,16,9]) in review articles, state that negligible amounts of water, if any, may enter the pores of the skin, or that the experimental evidence for any passage inward of water through the skin is poor. The view of these workers is curious in the light of the results from other laboratories and the ease with which the present study demonstrated water penetration. Rothman[36,37] stated that water and aqueous solutions do not enter the follicular and glandular pores under normal pressures because of insufficient wetting and because the ducts are filled with air. However, careful experiments by other workers have demonstrated that under normal pressure, water, as a vehicle for dyes or pharmacologic tracers, does penetrate at least the hair follicles and from there to the dermis and its capillary blood supply (MacKee,[21] Shelley,[39] Herman, cited by Shelley, and others). Their evidence combined with the results of the present experiments suggests that a cycle of fluid transfer occurs in the skin of the human foot. Perspiration is produced by glands and by diffusion, and the fluid may then be reabsorbed on the dorsum through hair follicles at a rate dependent upon the nearness of impermeable barriers. The pathway of penetration through the sole of the foot was not given particular attention but the most plausible route of reabsorption here is through sweat gland pores which are not secreting.[29,43] If the glands on the sole function only intermittently, as shown for other sweat glands by Randall,[32] then repenetration could occur during the inactive secretion period. Several authors have presented evidence that water can be absorbed in the duct or neck of sweat glands (MacKee,[21] Lobitz,[20] Sulzberger,[44] and Abramson[2]).

Studies recently reported by Peiss and co-workers[28] have indicated that the insensible water loss is greater on the palms and soles of the feet than on other skin areas and is apparently related to the high rate of blood flow in the palm and sole areas. The possible relation of the demonstration of this area of high diffusibility through a thickened cornified layer to the repenetration reported here will require further study.

An implication of the present findings on the penetration of water into the foot is that the skin of other areas of the body may also permit this penetration. Bazett[3] and others have failed to show the absorption of water by men sitting in baths, but the absorption from wet underwear[25] or other clothing has not been studied. If this is large, sweating as determined from loss of weight and thermal calculations based upon these losses may be in serious error because of the repenetration of sweat from underwear.

The composition of the penetrant received limited attention in this study because of the technical difficulties involved in critical experiments with electrolytes added to the water. A recent review article[9] considers the evidence from many sources and favors the view that the skin of man and the higher animals is relatively impermeable to electrolytes. The explanation is offered that the skin behaves like a charged membrane with a negative charge on the outside. Theoretically this membrane should be cation permeable and anion impermeable. If this is correct, one would expect a penetration of water and not of chloride in the experiments described in this report. Evidence was found consistent with this selective penetration in one series of experiments. When subjects wore a dry sock on one foot and a water-soaked sock on the other foot for several days, the chloride collections from the two socks appeared closely similar, which supports the interpretation of water penetration without chloride penetration. Studies of other ions and studies by other methods would, of course, be required for a definitive answer to this question.

6. Summary and Conclusions

a. Summary

The surprising fact that men can wear impermeable barriers or all-rubber shoepacs for several days without discomfort has been shown by Siple and Bazett,[41] Spealman,[42] Clinton,[10] Folk and Peary[13] and Blair.[6]

It was demonstrated in EPS Special Report No. 37, that the amount of moisture accumulated under an impermeable barrier was modified by the thickness of the absorbent layer between the skin of the foot and the impermeable barrier. The accumulation of foot perspiration is appreciably less when an impermeable barrier is worn outside one of the three pairs of socks (near barrier) than when the barrier is worn outside three pairs (far barrier). In some cases the accumulation under the far barrier was four or five times the accumulation under the near barrier.

The perspiration which accumulates in three socks under a far barrier, or in five socks, is only a part of the perspiration which would be evaporating from the foot if no sockgear were present. Probably the repenetration phenomenon takes place under other types of footgear as well as the impermeable sock. Furthermore, it was found that this phenomenon occurs when the hands are dressed in near barriers.

Wear of an impermeable barrier over a single sock is not associated with discomfort, the sock does not become saturated with moisture, and only small quantities of moisture can be found on the skin when the sock is removed. Apparently repenetration for several days does not alter the performance or comfort of the human foot. In one test eleven men wearing near and far barriers and shoepacs completed a strenuous mountain climb without appreciable discomfort to either foot. The impermeable barriers worn by four of the men for 48 hours prior to the climb had caused continuous repenetration during this period.

Evidence for the occurrence of repenetration under impermeable barriers was also obtained by prewetting the socks worn under impermeable barriers. One series with presoaking was carried out with 90 cc. of water in the socks at the beginning of the experiment. As much as 37 cc. of this water penetrated the skin during the ten-hour experimental period. These studies showed a measured penetration of approximately 1 cc. of water per hour from moderately wet socks into the feet of seated subjects, and a measured penetration of 2 cc. to 3 cc. per hour for eight to ten hours from wet socks with subjects walking part of the time. It was supposed that this measured penetration represented only one component of the actual value. The remainder would originate from continuous sweating which would supposedly increase the fluid content of wet socks unless penetration occurred. It is significant that 20 minutes after a wet and a dry sock were applied on opposite feet, the subject frequently could not detect a difference in sensation between the two feet.

The occurrence of repenetration under the near barrier could be established by evidence that sweating continued at its normal rate. Chloride analysis of perspiration collected in the socks was used as a measure of sweating. When subjects wore near barriers under three different types of conditions, tests for chloride secretion demonstrated that approximately normal sweating continues under the near barrier. When subjects wore a dry sock on one foot and a watersoaked sock on the other foot for several days, the chloride collections from the two socks appeared similar. The observations that sweat chlorides were collected in similar quantities: (1) in both wet and dry socks; (2) under near and far barriers; and (3) in a water bath compared with sock control values, suggest that sweating continues at normal rates under near barriers.

The measured vapor pressure in socks under both a near and a far barrier was in nearly all cases lower than the calculated vapor pressure in the associated skin tissue. Apparently with this footgear a complete suppression effect on the diffusion of insensible moisture does not usually occur.

Thus the relationships under the near barrier seem to be such that water in the sock, whether it originates from external sources, by accumulation from sweat glands, or as insensible moisture, comes to an equilibrium value in a few hours, apparently due to repenetration.

It is usually assumed that footwear designed for protracted wear must provide for evaporation of sweat. These studies have shown that evaporation is not essential inside a shoe, and that, therefore, footwear which preserves its insulation by virtue of being water impermeable on both the inside and the outside may be physiologically acceptable.

b. Conclusions

Penetration of water from wet socks into the foot has been demonstrated, explaining the acceptability of impermeable footwear.

Less sweat accumulates under an impermeable barrier which is placed near the foot (over one sock) than under a barrier placed at a greater distance from the foot.

As measured by sweat chloride, production of sweat is not suppressed by an impermeable barrier but continues at an approximately normal rate. The reduced accumulation reflects an equilibrium reached between production and repenetration.

Socks worn under impermeable barriers do not become excessively wet with sweat. The skin under such barriers does not become completely sodden, and discomfort is transient.

Preliminary studies of vapor pressure under different layers of socks indicate that the vapor pressure does not reach that calculated for tissue even though repenetration of moisture is occurring.

The phenomenon of repenetration probably occurs under leather footwear as well as under impermeable rubber or plastic barriers. Footwear maintaining insulation by virtue of sealed-in insulation is physiologically acceptable.

7. Recommendations

That further studies of the two-way passage of moisture through the skin be undertaken in relation to impermeable footgear, including studies at lower skin temperatures.

That these studies be extended to other areas of the body, especially as they may apply to the study of vapor barrier clothing.

That additional techniques be employed in studying the mechanisms of this surprising phenomenon. Particular attention should be given to the electrolytic composition of the water which repenetrates.

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Appendix A

Technique for Sealing Impermeable Barrier to Skin of Lower Leg.

The impermeable barrier used was a plastic pistol cover. The sealing materials were 2" wide, waterproof adhesive tape and collodion. The success of the seal depends entirely on the care with which it is affixed.

A necessary tool is some device which will stretch the mouth of the pistol cover entirely free of wrinkles and permit a strip of the adhesive tape to be firmly and smoothly affixed around the mouth, one inch of width adhering to the pistol cover and one inch of width projecting beyond and free from contact with anything. The tool which we used successfully was a strip of spring brass, 1/32" thick, 3" wide, and 22" long, bent to form a collar about 6-1/2" in diameter. The ends were free to slip past each other so that the collar could be compressed to a small enough diameter to be entered into the mouth of the pistol cover. Upon releasing it, the natural spring of the collar expanded it and gave the mouth of the pistol cover the requisite smoothness together with a firm backing for pressing the adhesive tape in place. Before we applied the tape, the pistol cover, under tension from the collar, was carefully smoothed out and adjusted so that 1/16" to 1/8" of cover projected beyond the edge of the collar. This last precaution was to make sure the adhesive tape did not stick to the collar. The ends of the tape were lapped about an inch. To remove the collar after the tape was in place, we compressed it, pistol cover as well, being very careful that the exposed edge of the adhesive did not come in contact with itself. When the collar was an inch or more smaller in diameter than the pistol cover, we gripped the two overlapping ends of the collar with long nose pliers, thereby preventing expansion until the collar had been withdrawn.

The pistol cover, as an impermeable barrier, was weighed after the adhesive tape was affixed. It is advisable to prepare the barriers immediately before use since the adhesive tape loses its effectiveness by exposure to air.

In applying the sealed barrier, all socks to be worn inside it should be cut off or turned down below the upper limit of the barrier. The subject's leg should be shaved and wiped off with alcohol where the adhesive is to be. Great care should be exercised when drawing on the barrier to keep the adhesive from rolling under itself. If this should happen, the chances for a perfect seal are greatly reduced. Slight contact between the adhesive and the socks during the process is not as bad as contact with the fingers of the person putting on the barrier.

When the barrier is in its proper place, the adhesive strip should be pulled tightly from front to back so that it is free from wrinkles, it makes smooth contact with both sides of the subject's leg and the surplus is about equally divided, half in front, half in back. The tape should then be pressed firmly and smoothly to the leg, starting at the middle of the sides and working towards front and back where two "fins" will be formed by the excess tape being stuck to itself. The joint between tape and leg is generously painted with collodion, the "fins" folded back along the leg and secured with a fair sized rubber band or string and the seal is complete.

If it is desirable to test the seal, a short length of rubber tube may be sealed in the outer end of one of the "fins" through which the barrier may be inflated. During the experiment, the tube may be clamped off to preserve the seal.

At the start of an experiment it seems best to inflate the barrier with an aspirator bulb so as not to introduce any moisture. At the end of an experiment, inflation by the mouth will minimize the loss of moisture.

APPENDIX B: A COMPARISON OF VAPOR PRESSURE MEASUREMENTS BETWEEN SOCK LAYERS WET WITH SWEAT AND WET WITH DISTILLED WATER, SHOWING A LACK OF TECHNICAL INTERFERENCE OF SWEAT UPON CAPSULE PSYCHROMETERS

Subject: RP
Conditions: Sitting in air-conditioned room at 80°F. and 50 percent Relative Humidity
Dress: "Far" or "Near" Barrier and Light Body Clothing

	Moisture in Socks at Time of Measurements			VP+ in Tissue (Calculated)	Diff.	VP+ Between Skin and CS Sock	Diff.	VP+ Between CS Sock and 1st Ski Sock or Barrier	Diff.	VP+ Between 1st Ski and 2nd Ski Sock	Diff.	VP+ Between 2nd Ski Sock and Barrier	Total VP+ Diff. Between Skin and Barrier
	CS Sock	1st Ski	2nd Ski										
FAR BARRIER - DORSUM													
Grams of Sweat	4.9	10.4	35.8	40.0	3.3	36.7	2.8	33.9	1.5	32.4	3.1	29.3	10.7
Grams of Distilled Water	4.5	10.8	36.0	43.0	4.7	38.3	1.6	36.7	0.9	35.8	2.8	33.0	10.0
NEAR BARRIER - DORSUM													
Grams of Sweat	11.4			38.2	1.7	36.5	1.3	35.2					3.0
Grams of Distilled Water	11.4			37.9	1.7	36.2	-0.3	36.5					1.4
NEAR BARRIER - SOLE													
Grams of Sweat	11.4			39.4	2.4	37.0	0.9	36.1					3.3
Grams of Distilled Water	11.4			38.6	2.5	36.1	0.1	36.0					2.6

+VP - Vapor Pressure - in mm. Hg.

APPENDIX C: COLLECTIONS OF INSENSIBLE AND NONTHERMAL MOISTURE IN SOLES AND DORSA OF SOCKS

(All Values in Grams of Perspiration)

Clothing:	Cotton Shorts, Socks, and Barriers.
Ambient Conditions:	64°F., 50 percent Relative Humidity.
Duration:	3-1/2 hours each experiment for four consecutive days.
Procedure:	Subjects seated. Feet soaked for thirty minutes in 0.9 percent saline, then washed in distilled water.

Subject: KS

	Left Foot ("Far" Barrier)					Right Foot ("Near" Barrier)				
Day	1	2	3	4	Total	1	2	3	4	Total
CS Sole	0.8	1.0	0.8	0.6	3.2	2.0	1.7	1.5	1.5	6.7
CS Upper	0.4	0.8	0.4	0.5	2.1	2.5	1.6	1.4	1.4	6.9
1st Ski Sole	1.4	0.9	0.8	0.7	3.8					
1st Ski Upper	1.3	0.9	0.8	0.7	3.7					
2nd Ski Sole	1.4	1.0	1.0	0.6	4.0					
2nd Ski Upper	2.0	1.3	1.1	0.7	5.1					
Total	7.3	5.9	4.9	3.8	21.9	4.5	3.3	2.9	2.9	13.6
Subject: LP										
Day	1	2	3	4	Total	1	2	3	4	Total
CS Sole	1.1	0.6	0.8	1.0	3.5	1.9	1.8	1.4	1.6	6.7
CS Upper	0.3	0.0	0.4	0.2	0.9	1.6	1.6	1.4	0.9	5.5
1st Ski Sole	1.0	0.9	0.9	0.6	3.4					
1st Ski Upper	0.9	0.8	0.5	1.0	3.2					
2nd Ski Sole	1.3	1.0	0.9	1.1	4.3					
2nd Ski Upper	1.6	1.0	0.8	1.1	4.5					
Total	6.2	4.3	4.3	5.0	19.8	3.5	3.4	2.8	2.5	12.2

APPENDIX D: VAPOR PRESSURES OF TISSUE FLUID AND WATER COMPARED

°F.	°C.	VP+ H_2O from Table in Chemistry and Physics Handbook	VP*+ Tissue	Δ VP+ of * H_2O and Tissue
78.8	26.00	25.21	24.00	1.21
79.0	26.11	25.37	24.16	1.21
80.0	26.67	26.22	24.99	1.23
81.0	27.23	27.10	25.85	1.25
82.0	27.78	27.99	26.72	1.27
83.0	28.34	28.91	27.62	1.29
84.0	28.89	29.85	28.54	1.31
85.0	29.45	30.83	29.50	1.33
86.0	30.00	31.82	30.47	1.35
87.0	30.56	32.86	31.50	1.36
88.0	31.11	33.91	32.53	1.38
89.0	31.67	35.00	33.60	1.40
90.0	32.22	36.12	34.70	1.42
91.0	32.78	37.27	35.82	1.44
92.0	33.33	38.44	36.98	1.46
93.0	33.89	39.66	38.18	1.48
94.0	34.44	40.90	39.40	1.50
95.0	35.00	42.18	40.66	1.52
96.0	35.55	43.48	47.94	1.54
96.8	36.00	44.56	43.00	1.56
97.0	36.11	44.83	43.27	1.56
98.0	36.66	46.21	44.63	1.58
99.0	37.22	47.63	46.03	1.60
100.0	37.78	49.10	47.48	1.62

*Underscored figures in these two columns are basic. Others are interpolations.
+VP - Vapor Pressure - in mm. Hg.

APPENDIX E: VAPOR PRESSURE DIFFERENCES BETWEEN VALUES CALCULATED FOR SKIN TISSUE AND MEASUREMENTS MADE BETWEEN SKIN AND INNER SOCK

(Data obtained at end of three hours of sitting in air-conditioned chamber. In some cases additional perspiration was collected in socks before experiment.)

Subject: RP	NEAR BARRIER				FAR BARRIER			
	Sole		Dorsum		Sole		Dorsum	
Hours of Wear of Socks	Grams of Perspiration in sock	+Vapor Pressure Difference	Grams of Perspiration in Sock	+Vapor Pressure Difference	Grams of Perspiration in Sock	+Vapor Pressure Difference	Grams of Perspiration in Sock	+Vapor Pressure Difference
3/4 hour	1.1	4.4	1.1	2.3	0.7	5.7		
1-3/4 hours	2.1	3.2	2.1	2.2	1.4	5.2		
2-3/4 hours					2.0	4.5		
3 hours							0.7	6.0
3-3/4 hours	3.4	3.5	3.4	2.4			1.4	4.6
4-3/4 hours					2.5	4.5	1.9	4.1
8 hours	4.8	5.1	4.8	3.6			2.4	4.2
11 hours	11.4	2.6	11.4	1.7			4.9	3.3
Equivalent of 24 hours of wear including exercise					12.8	2.3		
Subject: TK								
3/4 hour	1.7	2.7	1.7	1.8				
1-3/4 hours	3.2	3.0	3.2	3.0				
3 hours							1.2	4.6
3-3/4 hours	5.3	5.5	5.3	4.6				
6 hours							1.6	5.1
8 hours	7.4	5.4	7.4	4.9				
9 hours							2.0	4.4
12 hours							2.5	4.0

+Vapor Pressure - in mm. Hg.

APPENDIX F: VAPOR PRESSURE AND VAPOR PRESSURE DIFFERENCES AT FIVE LOCATIONS ON THE FOOT AT THE END OF EIGHT THREE-HOUR EXPERIMENTS

Dress: Near Barrier (one pair of socks) on both feet. Light body clothing.

Conditions: Sitting in air-conditioned room at 80°F. and 50 percent relative humidity

Subject: RP

Experiment		Center of Ventral Surface of Heel		Center of Ventral Surface of Ball		Center of Dorsum at Proximal End of 1st Metatarsal		Above Medial Malleolus		Center of Instep		Perspiration in Socks at End of Experiment (in Grams)
		VP+ in Tissue	VP+ Between Skin and Sock	VP+ in Tissue	VP+ Between Skin and Sock	VP+ in Tissue	VP+ Between Skin and Sock	VP+ in Tissue	VP+ Between Skin and Sock	VP+ in Tissue	VP+ Between Skin and Sock	
1		38.8	37.4	41.6	38.8	41.1	41.3	40.9	38.2			2.9
	Diff	1.4		2.8		-0.2		2.7				
2		33.8	34.3	40.0	36.3	38.8	37.2	37.2	35.2			3.6
	Diff	-0.5		3.7		1.6		2.0				
3		39.7	37.8	42.2	38.6	41.6	39.4	40.9	38.8			4.5
	Diff	1.9		3.6		2.2		2.1				
4		36.6	36.7	39.7	37.7	39.4	39.4	38.2	37.1			9.2
	Diff	-0.1		2.0		0		1.1				
5		38.2	39.2	41.9	40.5	40.7	39.3	38.8	37.7			9.1
	Diff	-1.0		1.4		1.4		1.1				
6										39.7	35.2	4.0
	Diff									4.5		
7										39.7	36.2	3.7
	Diff									3.5		
8										37.0	35.4	4.0
	Diff									1.6		

+VP - Vapor Pressure - in mm. Hg.

APPENDIX G: TYPICAL VAPOR PRESSURE STRATA IN SOCK LAYERS

Conditions: Measurements were made after subjects sat for 2-1/2 hours at 80°F. and 50 percent relative humidity.

Subject	Location of Measurement	Grams of Perspiration in Socks: CS Sock	Grams of Perspiration in Socks: 1st Ski Sock	Grams of Perspiration in Socks: 2nd Ski Sock	VP+ in Tissue (Calculated)	Diff.	VP+ Between Skin and CS Sock	Diff.	VP+ Between CS Sock and 1st Ski Sock or Barrier	Diff.	VP+ Between 1st Ski and 2nd Ski Sock	Diff.	VP+ Between 2nd Ski Sock and Barrier	Total VP+ Diff. Between Skin and Barrier
FAR BARRIER														
RP	Sole	2.5	4.7	7.1	41.1	4.5	36.6	1.6	35.1	2.5	32.6	2.3	30.3	10.8
TK	Dorsum	1.2	2.0	3.9	36.6	4.6	32.0	1.5	30.0	2.2	28.3	1.4	26.9	9.7
RP	Dorsum	1.4	3.2	5.5	39.4	4.6	34.8	2.3	32.5	2.5	30.8	2.4	27.6	11.8
RP	Dorsum	4.9	10.4	35.8	40.0	3.3	37.7	2.8	33.9	1.5	32.4	3.1	29.3	10.6
NEAR BARRIER														
RP	Sole	4.8			40.2	5.1	35.1	1.7	33.4					6.8
TK	Dorsum	7.4			43.3	4.9	38.4	2.3	36.1					7.2
RP	Dorsum	4.8			39.4	3.6	35.8	1.4	34.4					5.0
RP	Dorsum	11.4			38.2	1.7	36.5	1.3	35.2					3.0

+ VP - Vapor Pressure - in mm. Hg.

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